Jurnal Teknologi

Full Paper

NATURAL CONVECTION OF ALUMINIUM OXIDE-WATER NANOFLUID

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Article history
Received
15 February 2015
Received in revised form
10 March 2015
Accepted
27 March 2015

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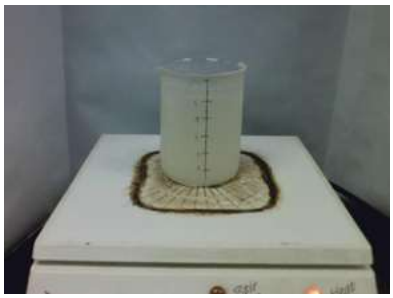
Graphical abstract



Abstract

As suspending nanoparticles in fluid-based give tremendous promise in heat transfer application, an understanding on the mechanism of heat transfer is indispensable. The present study dealt with natural convection of nanofluid inside a square cavity heated at the bottom, while the upper part was exposed to the atmosphere. Experimental studies have been performed for various physical conditions, such as volume fractions of nanoparticles varying from 0% to 2.0%, different dispersion techniques of nanoparticles in fluid-based, and heating time from 0 to 35 minutes. In general, dynamic viscosity of nanofluid clearly increased with volume fraction, but decreased with the increasing temperature. It was found that improper dispersion technique resulted in viscous solution. On top of that, transport mechanism of thermophoresis and Brownian diffusion were considered in analysing heat transfer across the cavity.

Keywords: Nanofluid; aluminium oxide nanoparticles; natural convection; transport mechanisms

Abstrak

Apabila menggunakan nanopartikel berasaskan cecair, ia mempunyai potensi yang luar biasa dalam applikasi pemindahan haba. Oleh itu, pemahaman mengenai mekanisme pemindahan haba adalah sangat diperlukan. Kajian ini adalah berkaitan dengan perolakan semulajadi nanofluid dalam rongga persegi yang dipanaskan di bahagian bawah, manakala bahagian atas terdedah kepada atmosfera. Kajian eksperimen telah dijalankan untuk pelbagai keadaan fizikal seperti pecahan jumlah nanopartikel yang berbeza; dari 0% hingga 2.0%, teknik penyebaran nanopartikel yang berasaskan cecair yang berbeza, dan masa pemanasan selama 0-35 minit. Secara umumnya, kelikatan dinamik nanofluid jelas meningkat dengan jumlah yang kecil, tetapi berkurangan dengan peningkatan suhu. Kajian ini juga telah mendapati bahawa teknik penyebaran yang tidak betul menyebabkan penyelesaian likat. Tambahan pula, mekanisme pengangkutan thermophoresis dan penyebaran Brownian telah dipertimbang dalam menganalisis pemindahan haba di seluruh rongga.

Kata kunci: Nanofluid; nanopartikel aluminium oksida; perolakan semulajadi; mekanisma pengangkutan

1.0 INTRODUCTION

The last few decades of the twentieth century have seen the world of research giving much emphasis on utilizing nano-size materials in various application like electronics, drug delivery, nuclear reactor, as well as communication and computing technologies as these particles possess unique characteristics like abnormal thermal conductivity enhancement, small concentration and Newtonian behaviour, particle size dependence, as well as high stability for over a month (Das et al., 2006). Meanwhile, as for cooling applications; completely focused on the employment of nanofluid in the systems gained when micro-sized particles fail to solve clogging of microchannel, erosion of components like heat exchangers, pipelines and pumps increase rapidly, as well as the increase in pumping power and settling of particles (Xuan and Li, 2000).

Since then, numerous researches have been conducted experimentally and various issues have arisen, both numerical and experimental, in determining the mechanism that could explain the behaviour of nanofluid solution. As for numerical approach, by assuming nanofluid solution is homogenous, some researchers only focused on physical properties of nanoparticles, e.g., particles size, diameter size, shape, and volume fraction of nanoparticles, in explaining the enhancement of thermal conductivity of colloid solution of nanofluid. However, for real, most researchers have to deal with stability of nanoparticles suspended in fluid-based, in the context of agglomeration and sedimentation process. Hence, the preparation of homogenous nanofluid has become a major challenge for researchers in optimizing special characteristics of nano-sized particles.

In fact, two methods are available in preparing nanofluid; i) the evaporation method in which nanoparticles are produced in fluid-based, and ii) powdered form of nanoparticles dispersed in liquid and for this process, physical treatment is needed for the purpose of reducing agglomeration process among nanoparticles and to achieve a long period of a stable colloidal solution (Hwang et al., 2008). Some examples of equipment used for physical treatment in nanofluids are stirrer, ultrasonic disruptor, ultrasonic bath, and high pressure homogenizer.

For instance, Mahbubul et al., (2014) used ultrasonic dispenser to disperse 0.5 vol% Al_2O_3-water for various durations from 0 to 180 min. They observed that by applying sonication time for a duration of 90 min and longer, better particle dispersion, smaller colloid sizes, less viscous, less sedimentation, and more stable nanofluids had been obtained. In the same way, Ruan and Jacobi (2014) claimed that extended sonication time could reduce agglomerate size of carbon nanotube and enhance thermal conductivity of 0.5 wt% carbon nanotube-EG nanofluid. By contrast, for 0.01 vol% of ZnO-EG nanofluid, Kole and Dey (2012) found that the cluster size of ZnO nanoparticles rapidly reduced from 459 nm to 91 nm for 4 to 60 h sonication time, however beyond 60 h cluster size growth to 220 nm.

Meanwhile, Kufner (2013) investigated the effects of various preparation methods on nanofluid properties. The author found that nanoparticles do not completely disperse and encourage particles to agglomerate and produce sediment when stirring method was adopted, but contradicting results were obtained when using sonication method. In another experiment, Angel-Lopez et al., (2014) studied the effects of preparation time on dispersion behaviour of nanocomposite. They stirred nanocomposite for 1, 3, and 5 h, while the sonication method was carried out for 30, 60, and 120 min. Moreover, the authors claimed that the dispersion of ZrO2 and SiO2 nanocomposites using sonication technique did not only improve the homogeneity and the dispersion properties of the particles, but also reduced the time for preparation of nanocomposites compared to mechanical stirring, even though the stirring time was longer than the sonication time. Furthermore, evaluation using SEM microscope conducted by Katamipour et al., (2014) indicated that the agglomeration of nanoparticles almost disappeared when sonication method was employed, besides magnetic stirring. On top of that, Wozniak et al., (2013) reported that the dispersion of aluminium nitride nanoparticle in polypropylene glycol using magnetic stirrer was ineffective as the solid particles tended to produce sediment after 30 h and the sedimentation rates were found greater than 90%

Apart from that, Hwang et al., (2008) studied the influence of various physical treatment techniques based on a two-step method, including stirrer, ultrasonic bath, ultrasonic disruptor, and high pressure homogenizer on the stability of carbon black (CB)-water nanofluids. The authors concluded that the most efficient technique to produce a stable colloidal structure of CB-water nanofluid was by using high pressure homogenizer treatment, followed by ultrasonic disruptor, and then, ultrasonic bath, while the employment of stirring technique showed no appreciable change in particle morphology, just like without any physical treatment. Meanwhile, Chung et al., (2009) concluded that the dispersion technique of ZnO in water using ultrasonic disruptor was more effective than ultrasonic bath in the context of reduction cluster size and sedimentation rate for ZnO nanoparticles.

However, in certain cases, these physical treatments had been incapable in promising heavy nanoparticles from sediment to the bottom. Therefore, surface active agent or surfactant was dispersed together with nanoparticles in liquid. Surfactant has been used by most researchers to modify hydrophobic part of nanoparticles or nanotubes to become hydrophilic in aqueous solution and vice versa for non-aqueous solution (Li et al., 2008). Another purpose of introducing surfactants is to hinder re-agglomeration process between nanoparticles in colloid solution. Examples of surfactants that are portrayed in literature are sodium dodecylsulfate (SDS) (Hwang et al., 2008), SDBS (Zhu et

al., 2009; Wang et al., 2009), salt and oleic acid (Ding et al., 2007), dodecyl trimethylammoniumbromide (DTAB) (Madni et al., 2010), hexadecyltrimethylammoniumbromide (HCTAB), and polyvinylpyrrolidone (PVP) (Goel & Rani, 2012).

2.0 EXPERIMENTAL

Table 1 shows the thermos-physical properties of water and aluminium oxide (Al_2O_3) nanoparticles. The primary size of Al_2O_3 nanoparticles is 30 nm in spherical shape. The nanoparticles volume fraction dispersed in water-based fluid had been varied from 0.5 vol.% to 2.0 vol.%. Since the present study investigated the influence of physical treatment towards viscosity trend of nanofluid solutions, two different techniques of manual stirrer and mechanical stirrer (Model IKA RW20 digital) had been adopted in order to achieve the objective. As for mechanical stirrer, the stirring process was carried out at a constant test condition of 360 rpm revolution speed and 40 min of revolution time. Besides, in order to study the thermal behaviour of Al_2O_3-water nanofluid solution, thermal imager (Model Fluke Ti200) was used to capture the image of heat distribution within the system. During the heating process, the stationary state of nanofluid was injected with a constant heat flux using a hot plate for a duration of 35 minutes, as shown in Figure 1. The square cavity was heated at the bottom and it was exposed to the atmosphere at the upper part.

Table 1 Thermo-physical properties of water and Al_2O_3 particles.

Physical properties	Water	Al_2O_3 nanoparticles
Density (kg/m3))	997.1	3700
Viscosity (N.s/ m2	0.001004	-
Specific heat (J/kg.K)	4179	765
Thermal conductivity (W/m.k)	0.6248	40

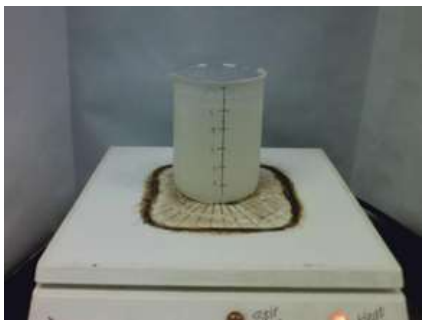


Figure 1 Experimental set up during heating process.

Therefore, this prospective study was designed to investigate the most favourable preparation method to disperse nanoparticles in fluid and to study the behaviour of heat distribution in a system that contained nanoparticles.

3.0 RESULTS AND DISCUSSION

3.1 Stability Of Nanofluid Solution

Figure 2 below shows the visual observation done for each particle volume concentration of 0.5%, 1.0%, 1.5%, and 2.0% on the 1st day, 3rd day, 5th day, and 20th day. The suspension of Al_2O_3 nanoparticles in water was prepared via conventional method. From the figure, no significant change was observed at the bottom of the bottles on the 1st and the 3rd day for all volume concentrations. However, there was obvious settlement of white powder at the bottom that appeared for each concentration on the 5th day, and the settling rate was slow. As seen from the images, on the 20th day, the sedimentation process between volumes of concentrations was conspicuous, and thus, the sedimentation rate decreased with the increasing in particle volume concentration.

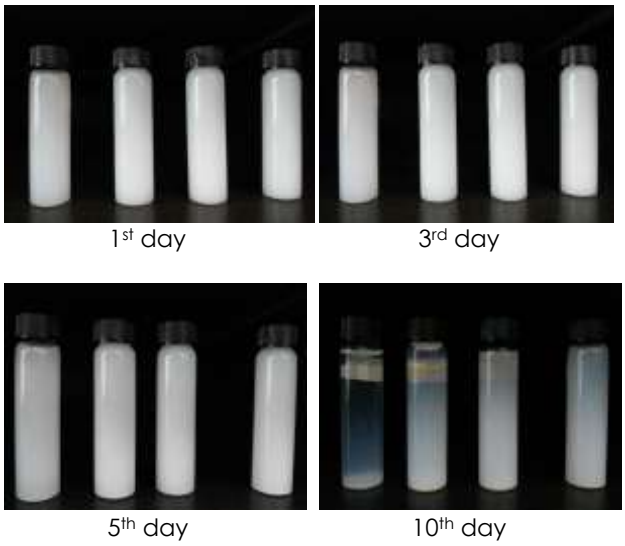


Figure 2 Stability of Al_2O_3-water nanofluid solution via visual observation.

The explanation for the nanoparticles to settle at the base in the fluid had been due to the gravitational force that was exerted on the particles. According to Stoke's settling theory in equation 10, gravitational acceleration and viscous force are the forces that urge particles to settle down. From the equation, the settling velocity was proportional to the diameter of the particles and this was somehow troublesome as these particles had the tendency to agglomerate into huge sizes. Other than that, as for natural convection, the probability of particles settling was very high due

to the stationary nature of the bulk fluid, and thus, this unwanted process might increase thermal resistance and posed as a burden to the system instead of bringing enhancement (Witharana, 2011).

$$U_t = \frac{d_2(\rho_s - \rho)g}{18\mu} \quad (1)$$

3.2 Viscosity Of Nanofluid Solution

Viscosity tests, which had been carried out for different techniques of preparation methods, are shown in Figures 3 and 4. As illustrated in the figures, the viscosity of Al_2O_3-water nanofluid decreased with the increase in temperature, but increased with the increase in particle volume concentration for each preparation method. However, the data on viscosity for manual stirring method were apparently higher for each volume concentration than those that employed the mechanical stirring method.

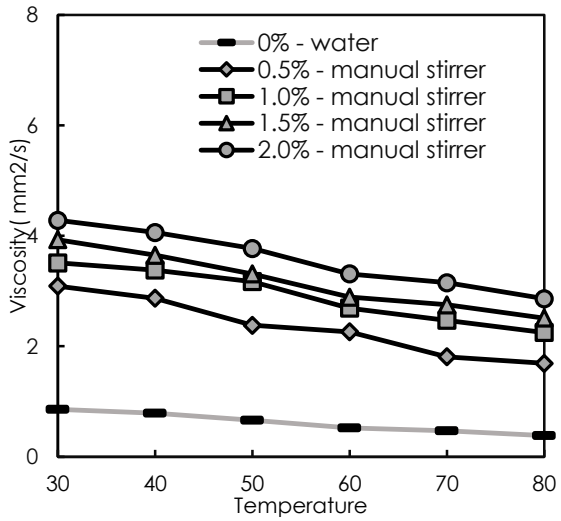


Figure 3 Viscosity of nanofluid solution prepared by using manual stirrer.

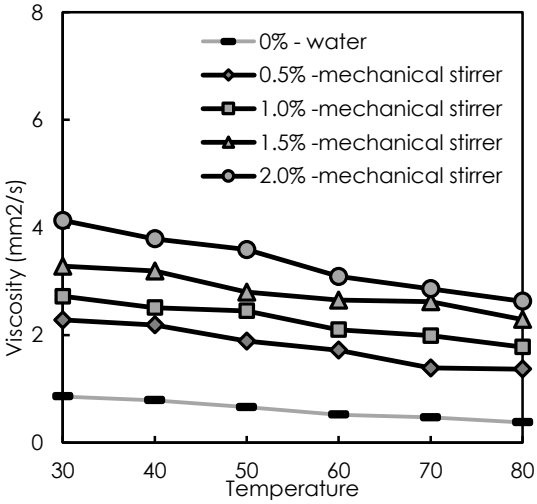


Figure 4 Viscosity of nanofluid solution prepared by using mechanical stirrer.

From the measurement of data viscosity, it showed that the conventional method was not an effective method in reducing the huge size of agglomerate particles and failed to promote a homogenous solution. Nevertheless, mechanical stirring and manual stirring promote the same whirling effect on the bulk nanofluid, as mechanical stirring could generate aggressive mixing and faster rotation of vortex, and hence, sufficient to break apart the huge aggregate structures into isolated particles. The result of viscosity with the increase of volume concentration was because by increasing the amount of particles suspended in the fluid might increase the number of aggregate structures with different sizes in nanofluid solution (Pastoriza-Gallego et al., 2011) and this directly increased the shear stress in bulk nanofluid.

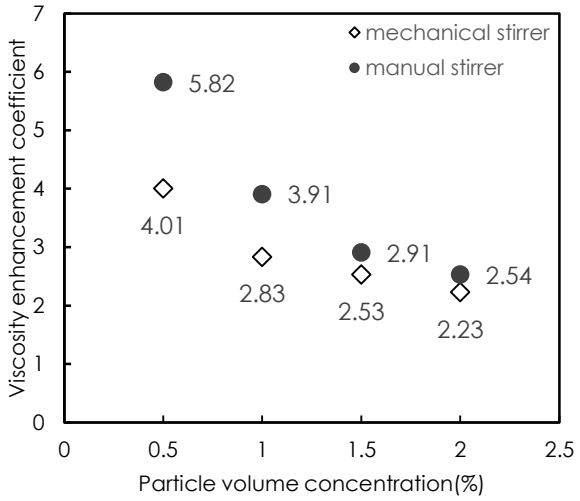


Figure 5 Viscosity enhancement coefficient for nanoparticles with varying volume fractions.

From the graph, the higher value of nanofluid viscosity than water had been worrisome as this behaviour could drop the pressure lower than can a conventional coolant do in any system. As reported by most researchers, the increment in viscosity with particles concentration was in line with increment in thermal conductivity. From the experimental results, introduced a correlation to relate these increments and given as

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + C_\mu \cdot \phi \quad (2)$$

$$\mu_{nf} / \mu_{bf} = 1 + C\mu\ \phi \quad (3)$$

where $C\mu$ and C_k are viscosity and thermal enhancement coefficients. They claimed that most researchers reported the value of C_k was 5. From the measurement data of viscosity, it was found that the value of $C\mu$ for each particle concentration was lower than C_k, as shown in Figure 5. It showed that an

increase in viscosity was not large enough as compared to thermal conductivity, and thus, it might create a great benefit in using nanofluid as heat transfer fluid in real application.

3.3 Heat transfer of nanofluid solution

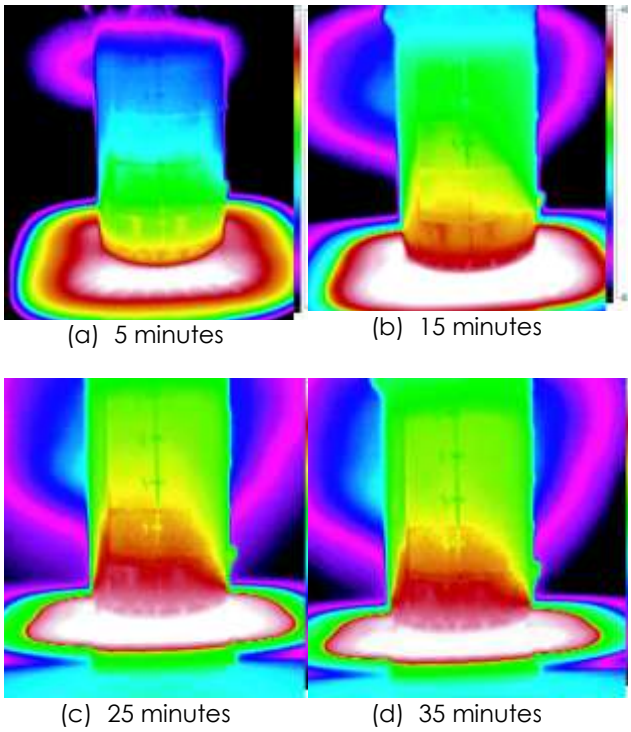


Figure 6 Heat distribution of Al_2O_3-water nanofluid for 0.5 vol. % (a) 5 minutes (b) 15 minutes (c) 25 minutes and (d) 35 minutes while heating at constant heat flux.

Heat distribution of Al_2O_3-water nanofluid with volume concentration of 0.5% in the square cavity at various durations is depicted in Figure 6. From Figure 6, it can be seen that the red contour, which exhibited the highest temperature, spread aggressively for the first 15 minutes, together with green and yellow contours. If the heating process was further extended, red and white contours dominated the heat distribution, while the low temperature contour vanished; like the blue contour, which vanished completely before reaching 25 minutes.

The enhancement of heat distribution of nanofluid from minute to minute, either with faster or slower rate, was contributed by the strong interparticle forces of interaction potential force and Brownian force between nanoparticles, as well as fluid. As the nanofluid solution underwent the heating process right after the preparation procedure, the stability of the solutions had been homogenous, as illustrated in Figure 2. So, the interaction forces between the nanoparticles were strong enough to hinder the re-agglomeration and the sedimentation processes, besides keeping the particles well-dispersed in fluid. In addition, when temperature differs in any system, migration of nanoparticles from hotter regions to colder regions, which is driven by Brownian force and the greatest collision impact between particles, could enhance heat transfer of nanofluid by interfering with the flow boundary layer and the thermal boundary layer of the system (Madler and Friedlander, 2007; Qi et al., 2013).

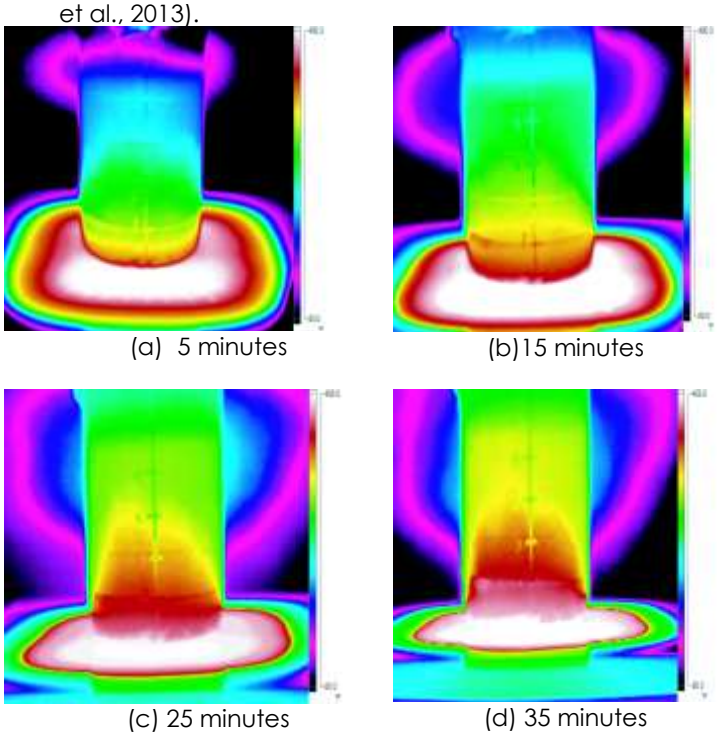


Figure 7 Heat distribution of Al_2O_3-water nanofluid for 1.5 vol. % (a) 5 minutes (b) 15 minutes (c) 25 minutes and (d) 35 minutes while heating at constant heat flux.

However, as depicted in Figs. 6 and 7, the spreading rate of red and yellow contours from 25 minutes to 35 minutes was a bit slower for both concentrations and this occurred due to the thermophoresis effect. As expected, when there was a temperature gradient in a particulate system, the migration of nanoparticles from hotter regions to the colder regions by driving force would eventually lead to the augmentation of nanoparticles in volume fraction in those colder regions. However, the dispersion rate of nanoparticles in colder regions is very slow (Efstathios, 2013). This behaviour of nanoparticles contributes to the retardation of heat transfer as low quantity of active nanoparticle volume fraction in hotter regions, while the accumulation of nanoparticles in the colder regions indicated that the thermophoresis effect is stronger than the Brownian diffusion (Sheikhzadeh et al., 2013; Aminfar et al., 2012; Qi et al., 2013). However, thermophoretic force is weakened when gravitational force dominates the nanoparticles.

The same behaviour of heat distribution was obtained for 1.5 vol. % of Al_2O_3-water nanofluid, as shown in Figure 7. Furthermore, as seen in Figure 7, the distribution of heat for 1.5 vol. % had been rather fast compared to that of 0.5 vol. %, especially at 25

minutes onwards. This had been due to the high volume fraction of nanoparticles in nanofluid solution, and hence, more nanoparticles were actively involved in the heat distribution process.

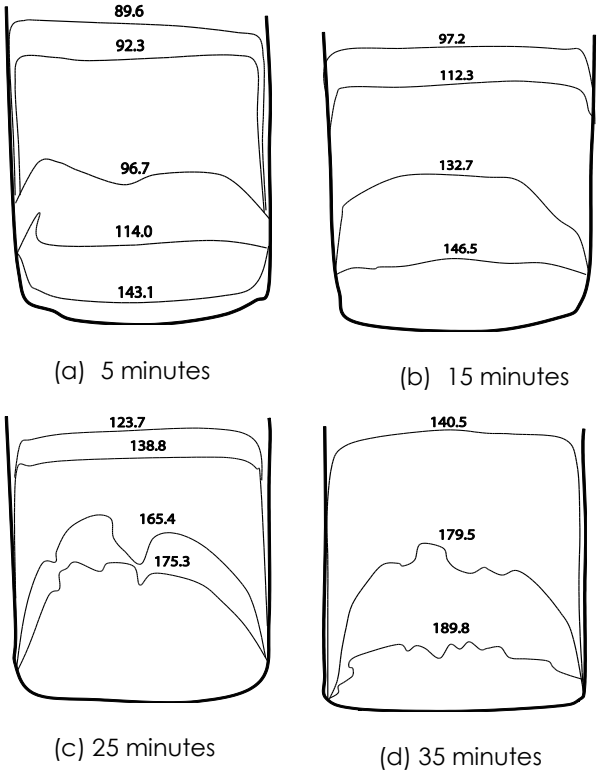


Figure 8 Isotherms of heat for 0.5 vol. % at varying durations (a) 5 minutes (b) 15 minutes (c) 25 minutes and (d) 35 minutes.

Figures 8 and 9 show the isotherms of heat distribution for 0.5 vol.% and 1.5 vol.% of Al_2O_3-water nanofluid. It can be seen that for both figures, the isotherms were less crooked for the first 15 minutes of heating process and the trend was conspicuous for the isotherms near the heating source. It explains that the transformation of heat from conduction to convection was a little slower usually caused by the difference in velocity between aluminium oxide nanoparticles and water molecules. The addition of nanoparticles in fluid might reduce the velocity of nanofluid solution in the square cavity as the nanofluid solution can become more viscous compared to solely water (He et al., 2011).

At earlier heating process, the Brownian movement of nanoparticles was lethargic and moved with settling velocity. This motion of nanoparticles, somehow, escalated a drag force in nanofluid solution, which resulted in the attenuation of convection heat transfer rate (Qi et al., 2013). As the heating process was further extended, the state of nanoparticles was in vigorous motion, and consequently, making the isotherms to become more crooked for both volume fractions exhibited the enhancement of natural convective heat transfer.

However, with the increase in heating time, the isotherms away from the heating source were nearly smooth without a crook. This was because; in these regions, the rate of natural convection was very weak and the conduction became a dominating mechanism for heat transfer. Thus, the natural convective heat transfer of Al_2O_3-water nanofluid decreased with the increased distance from heat source (Pakravan et al., 2013). Besides, the difference in temperature for both volume fractions was large and it increased with time. Moreover, the line of isotherms reduced with the increase in heating time. Besides, the vigorous movement of nanoparticles had a huge impact on thermal behaviour of nanofluid as it increased the penetration of heat, and hence, decreased the thermal boundary layer between the two regions of hot and cold.

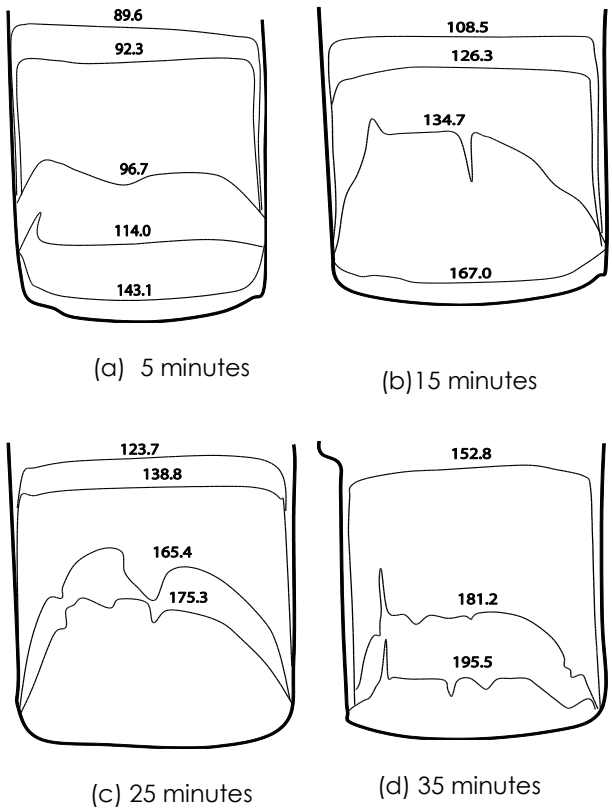


Figure 9 Isotherms of heat for 1.5 vol. % at various durations (a) 5 minutes (b) 15 minutes (c) 25 minutes and (d) 35 minutes

4.0 CONCLUSION

The present study investigated the influence of different dispersing methods on viscosity and heat transfer characteristics of Al_2O_3-water nanofluid

solution under natural convection inside a cavity being heated at the bottom, while the upper part was exposed to the atmosphere respectively. The nanofluid appeared to behave homogenously until the 5th day and the sedimentation layer of white powder thickened from the 5th day onwards. Besides, it was found that different dispersing techniques of nanoparticles affected the viscosity of the solution and inappropriate techniques caused the solution to be more viscous. Moreover, during the heating process, it was found that the heat transfer rate, which was exhibited by different contours and colours, increased with time, however, when reaching certain time, the rate became slower for both volume fractions of 0.5% and 1.5%. As heating time increased, the amount of isotherm lines decreased and they became more crooked. Meanwhile, high volume fraction of nanoparticles in 1.5 vol.% nanofluid solution induced augmentation of heat distribution within the system. For both nanofluid solutions, nanoparticles transport mechanism of thermophoresis effect, Brownian diffusion, and convection had crucial roles in explaining the behaviour of heat distribution across the system.

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